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Meteorological Events That Produced the Highest Ground-Level Concentrations during Complex Terrain Field Experiments

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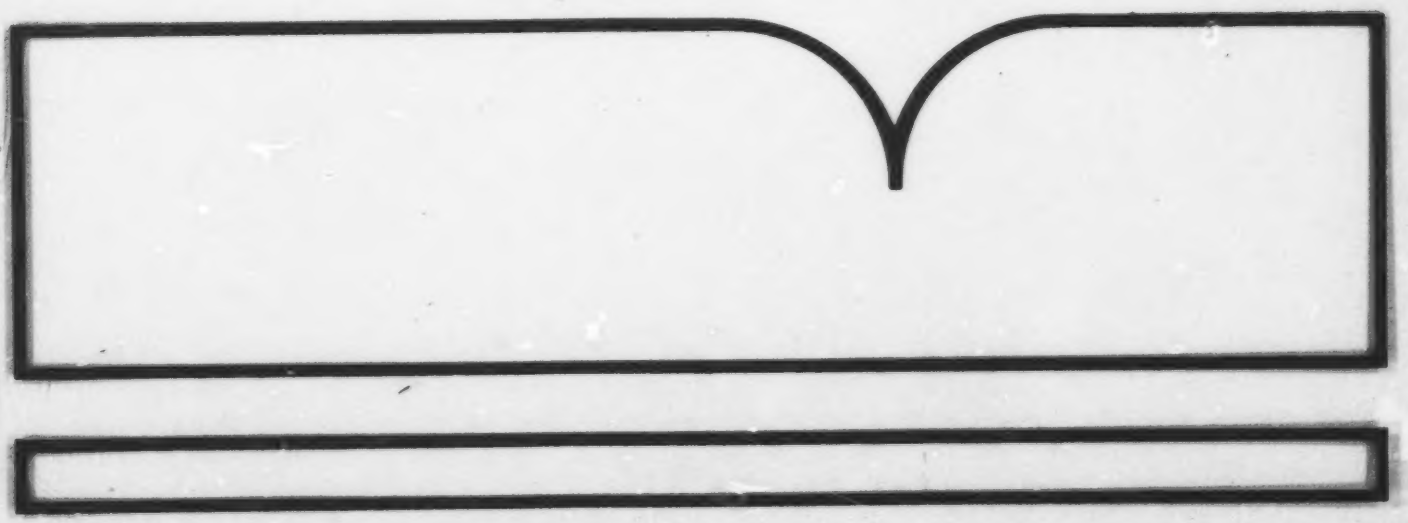

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16. ABSTRACT The U.S. Environmental Protection Agency (EPA) is sponsoring the Complex Terrain Model Development project, a multi-year study to develop improved models for calculating ground-level air pollutant concentrations that result from large emission sources located in mountainous terrain. The project started with tracer and flow visualization experiments and fluid modeling for isolated, simple terrain features -- Cinder Cone Butte (CCB), Idaho and the Hogback Ridge (HBR), New Mexico -- and has progressed to the Full Scale Plume Study (FSPS), conducted at the Tracy Power Plant near Reno, Nevada during August 1984.

The CCB and HBR experiments and related fluid modeling have demonstrated the usefulness of the concept of a dividing-streamline height (Hs) in discriminating between essentially horizontal flow that goes around the sides of the terrain features and flow that goes up and over the terrain. An analysis of tracer gas concentrations observed at CCB and HBR showed that the highest concentrations occurred during direct impingement of plumes released at elevations near the height of the dividing streamline. Releases well below Hs moved around the sides of the terrain and produced relatively low concentrations. Releases above Hs tended to travel over the terrain and produced ground-level concentrations near the peak or on the lee side. This paper illustrates the meteorological conditions that produced the highest tracer gas concentrations at CCB and HBR.

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METEOROLOGICAL EVENTS THAT PRODUCED THE HIGHEST GROUND-LEVEL CONCENTRATIONS DURING COMPLEX TERRAIN FIELD EXPERIMENTS

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INTRODUCTION

The U.S. Environmental Protection Agency (EPA) Complex Terrain Model Development (CTMD) program is a multi-year study to develop, evaluate, and refine models for calculating ground-level air pollutant concentrations that result from large emission sources located in mountainous terrain. Presently, the focus of the program is to develop models for simulating one-hour average plume impingement concentrations during stable atmospheric conditions.

The objectives of the program were described by Holzworth (1980) and generally follow the recommendations of the participants of the EPA sponsored workshop to consider the issues and problems of simulating air pollutant dispersion in complex terrain (Hovind et al., 1979). The program was subsequently designed with a perspective toward modeling and includes model development efforts based on physical modeling, field experiments, and theoretical work (Schiermeier, 1984).

The first major field program was a tracer and flow visualization experiment conducted during the fall of 1980 at Cinder Cone Butte (CCB), a roughly axisymmetric, isolated 100-m tall hill located in the broad Snake River Basin near Boise, Idaho. The field program (Lavery et al., 1982; Strimaitis et al., 1983) consisted of ten flow visualization (oil-fog) experiments, followed by 18 multi-hour combined tracer gas (SF_6, CF_3Br) and visualization experiments with supporting meteorological, lidar, and photographic measurements.

The second experiment was conducted during October 1982 at the Hogback Ridge (HBR) near Farmington, New Mexico. The field study was conducted in the vicinity of an approximately 1.5 km long section of the ridge which is oriented NNE-SSW and rises about 90 m above its base elevation. The HBR study (Lavery et al., 1983) included tracer and flow visualization experiments with concurrent meteorological, lidar, and photographic measurements.

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*On assignment from National Oceanic and Atmospheric Administration.

The experiment produced approximately 179 tracer hours and extended the modeling data base to include flow and dispersion around a two-dimensional ridge.

The Full Scale Plume Study (FSPS) was conducted at the Tracy Power Plant near Reno, Nevada in August 1984. The Tracy station was selected based on a feasibility study conducted at the site in November 1983 (Strimaitis et al., 1984). The power plant is located about 27 km east of Reno in the Truckee River Valley which is a relatively narrow valley with mountains surrounding the plant on all sides. Mountain peaks rise to elevations of 900 m above the stack base elevation within 6.5 km of the plant. The plant has three units of 53, 80, and 120 megawatts, although only the latter has been used recently. The 120-megawatt unit is serviced by a 91.4-m stack which was used to release the oil-fog and SF_6 during the experiment. The CF_3Br tracer gas was released from a 150-m meteorological tower located about 1.2 km east of the Tracy stack. The Tracy experiment, which was similar in design to the CCB and HBR studies, included tracer and flow visualization experiments with concurrent meteorological, lidar, and photographic measurements. The experiment produced approximately 258 tracer hours and extended the modeling data base to include flow and dispersion around a full-scale mountainous site.

The purpose of this paper is to illustrate the meteorological conditions that produced the highest ground-level concentrations during each field experiment. This paper also shows the applicability of the dividing-streamline concept to describe stable flow in complex terrain.

STABLE FLOW IN COMPLEX TERRAIN

For an ideal flow with a constant velocity U and Brunt-Vaisala frequency N approaching a hill of height h, the dynamic features of the flow around the hill are described by the hill Froude number (Fr), defined by

$$Fr = U/Nh \tag{1}$$

In physical terms, the hill Froude number is the square root of the ratio of the kinetic energy of the approaching fluid to the potential energy it acquires in surmounting the hill. The stability of the flow is described in terms of the local Brunt-Vaisala frequency defined by

$$N = [(g/\Theta)(\partial\Theta/\partial z]^{1/2} \tag{2}$$

where $\partial\Theta/\partial z$ is the stable potential temperature gradient (assumed to be uniform over the height of the hill), Θ is the potential temperature, and g is the acceleration due to gravity.

Experiments and theory (Sheppard, 1956; Drazin, 1961; Hunt and Snyder, 1980; Snyder et al., 1980; Rowe et al., 1982; Snyder and Hunt, 1984) indicate that when the lapse rate is constant and the wind speed is uniform over the hill, the Froude number can be used to define the critical or dividing-streamline height (Hc) as

$$Hc = h\ (1 - Fr) \tag{3}$$

Sheppard (1956) suggested a more general expression for determining Hc based upon kinetic/potential energy exchange arguments

$$\frac{1}{2}\rho U^2 = g\int_{H_c}^{h} (h-z)(-\partial\rho/\partial z)dz \tag{4}$$

where U is evaluated at Hc and $(\partial\rho/\partial z)$ is the local density gradient. The left-hand side of Equation 4 is the kinetic energy of a fluid parcel at this critical height, and the right-hand side is the potential energy gained by the fluid parcel rising through the height h-Hc. Thus, Hc is the height at which the fluid has just enough kinetic energy to ascend the hill.

The two distinct regions of flow around a typical hill are shown in Figure 1. In region 1, which extends from the base of the hill to Hc, the flow does not have enough kinetic energy to surmount the hill and remains roughly horizontal as it impinges, splits, and goes around the hill. This flow separates into a recirculating wake on the downwind side. In region 2, the flow which is above Hc has enough energy to pass up and over the hill. The concept of Hc is related to the belief that a fluid parcel can rise only through a height U/N. As defined, Hc depends only on the height of the hill; it does not account for the shape of the hill as "seen" by the flow.

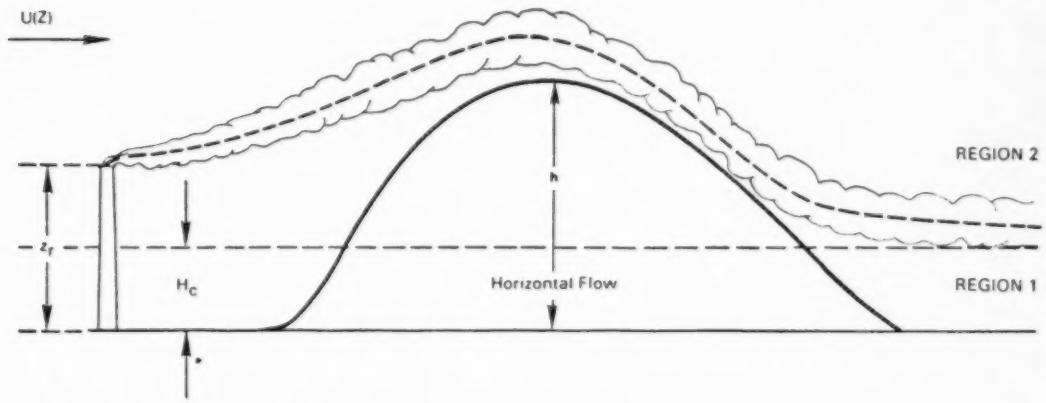

Figure 1. Schematic of plume behavior in stable flows around obstacles.

HIGHEST TRACER GAS CONCENTRATION MEASUREMENTS

Cinder Cone Butte

The ten highest observed SF_6 concentrations scaled by emission rates (shown as normalized χ/Q) measured at CCB are presented in Table 1. The net release height (Zr), dividing streamline height (Hc), sampler elevation (Zmax), wind speed (U), sigma-v (σ_v), sigma-w (σ_w) all estimated at Zr, Brunt-Vaisala frequency (N), and the downwind distance of the sampler (d) are also listed. Typically, the highest concentrations occurred when Zr ~ Hc, with Zmax < Zr. Releases well below Hc tended to remain roughly horizontal and travel around the sides of the hill, producing relatively low ground-level concentrations. Releases above Hc flowed up and over the hill and produced concentrations near the top or on the lee side of CCB.

The distribution of the observed hourly averaged SF_6 concentrations ($\mu s/m^3$) for Experiment 206 Hour 8 is shown in Figure 2. A 10-m contour interval is shown starting with 5 m. The SF_6 tracer gas and oil-fog were released southeast of the hill at a release height 35 m above the ground. Local terrain elevations near the release point are estimated to be 5.5 m below the base elevation of the hill coordinate system, so the net release height corresponds to the 29.5-m height level on the hill. Large directional wind shear was observed between the surface and plume elevation.

Table 1. Ten Highest χ/Q Observed SF_6 Concentrations at CCB

Exp No.	Hour End	χ/Q ($\mu s/m^3$)	Zr (m)	Hc (m)	Zmax (m)	U(Zr) (m/s)	σ_v(Zr) (m/s)	σ_w(Zr) (m/s)	N (1/s)	d (m)
206	08	164.0	30	33	25.3	1.8	.196	.155	.0372	300
214	09	120.0	22	7	30.0	2.7	.533	.278	.0266	353
206	06	115.0	30	33	25.3	1.8	.209	.134	.0347	300
214	05	103.0	15	39	-3.5	1.6	.691	.206	.0653	556
211	05	98.3	11	21	30.0	2.3	.408	.163	.0738	973
206	07	90.3	30	27	31.2	2.4	.208	.142	.0362	437
217	04	85.7	23	0	77.0	5.1	.230	.104	.0289	1089
203	08	83.8	43	36	-2.4	3.4	.449	.181	.0452	160
203	06	83.3	20	40	-2.4	1.0	.230	.091	.0631	394
214	08	73.8	22	18	30.0	2.2	.271	.164	.0470	243

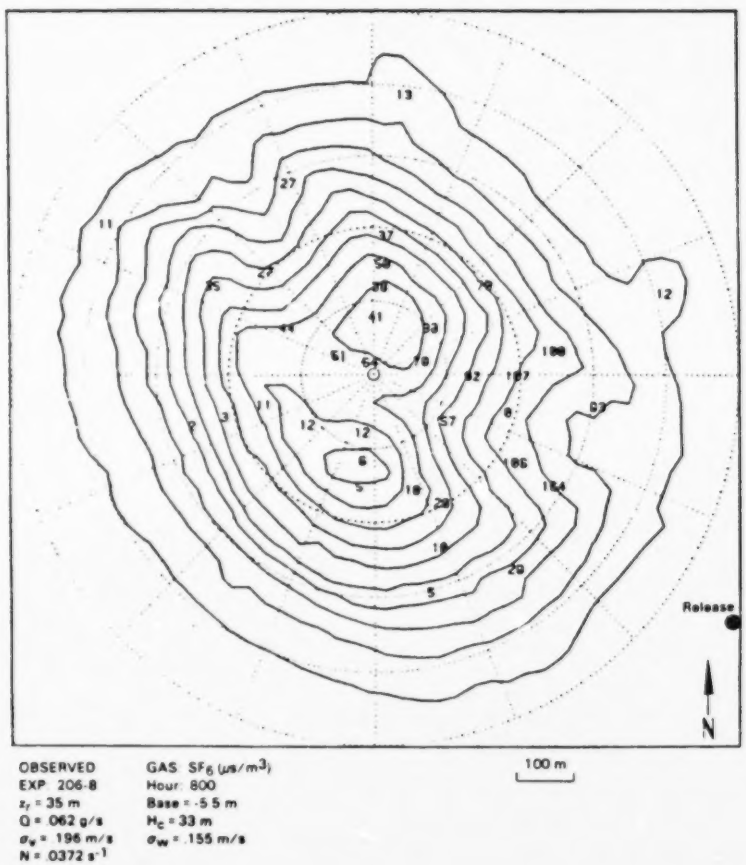

Figure 2. One-hour average observed SF_6 concentrations scaled by emission rate ($\mu s/m^3$). Experiment 206, 24 October 1980, 0700-0800 MDT.

The hourly averaged Hc value is 33 m; thus, this hour represents transport along streamlines very near Hc in a complicated flow with substantial shear below Hc. Observations indicate that the plume mixed down to the hill surface near the base of the draw on the southeast side of CCB producing the maximum observed SF_6 concentration (164 $\mu s/m^3$) at an elevation (25.3 m) less than Hc. Concentrations are also found on the northeast and

north sides of the butte. Plume material was mixed to the surface of the hill and then advected directly over and around the hill.

Table 2 lists the ten highest observed CF_3Br concentrations (as normalized χ/Q) measured at CCB along with the appropriate release and meteorological information. The highest CF_3Br concentrations occurred when the release height was above the calculated dividing-streamline height. Typically, the peak concentrations were observed at elevations higher than the release height. Four of the highest ten concentrations were observed during the neutral Experiment 217 (Hc = 0). Evidently, there was enough mixing (note the values of σ_w) to bring the CF_3Br plume to the hill surface near an elevation of 15 m.

Table 2. Ten Highest χ/Q Observed CF_3Br Concentrations at CCB

Exp No.	Hour End	χ/Q ($\mu s/m^3$)	Zr (m)	Hc (m)	Zmax (m)	U(Zr) (m/s)	σ_v(Zr) (m/s)	σ_w(Zr) (m/s)	N (1/s)	d (m)
210	07	75.3	22	11	50.0	5.1	.594	.361	.0388	1060
217	07	64.6	8	0	11.8	4.6	.262	.286	.0200	869
217	08	55.2	8	0	11.8	4.4	.262	.234	.0171	869
210	06	47.5	22	5	50.0	5.5	.225	.155	.0348	944
216	02	36.1	43	7	32.9*	3.6	.441	.123	.0191	1289
214	04	34.4	38	27	99.0	2.8	.338	.145	.0281	709
210	03	32.7	23	22	46.9	3.9	.356	.104	.0591	1003
213	06	30.4	51	45	90.9	3.1	.254	.142	.0465	1099
217	09	25.4	8	0	30.0	5.2	.447	.239	.0256	1270
217	10	24.6	8	0	22.1	5.1	.502	.400	.0087	945

*Concentration measured in lee of CCB.

Table 2 contains one CF_3Br release (Experiment 210 Hour 3) at CCB near the dividing-streamline height. The results of this case are similar to CF_3Br releases above Hc in that the highest concentration occurred at an elevation higher than the release height. Releases well below Hc produced relatively lower concentrations on CCB.

Hogback Ridge

The ten highest SF_6 concentrations (as normalized χ/Q) measured at HBR are presented in Table 3. The highest concentrations occurred when Zr > Hc. At HBR the SF_6 was released coincidentally with the oil-fog through the nozzle of the jet fogger. Because of the very light winds that were typical below the crest of the ridge and the thermal buoyancy of the oil-fog release, the coincidental SF_6 and oil-fog plumes frequently rose well above Hc. As observed at CCB, these plumes above Hc flowed up and over the ridge producing the highest concentrations at Zmax > Zr, typically near the top or on the lee side of the ridge.

The distribution of the observed hourly averaged SF_6 concentrations ($\mu s/m^3$) for Experiment 7 Hour 7 is shown in Figure 3. The SF_6 tracer gas and oil-fog were released 100 m from the base of the ridge at a release height 15 m above the ground. The oil-fog generator produced enough heat flux to cause a thermally-induced rise in the oil fog and co-located SF_6 plumes. Lidar measurements taken near the source, meteorological profiles, and photographs were used to estimate a 32 m plume rise. Thus, the

effective plume elevation after plume rise is 47 m above the ground. Local terrain elevations near the release point are estimated to be 17.4 m above the base elevation, so the net release height corresponds to the 64.4 m level on the ridge. The hourly averaged Hc value estimated at the 150-m meteorological tower (Tower A) is 41 m; thus, this hour represents flow above Hc. The maximum observed CF_3Br concentration (92 $\mu s/m^3$) is found in the lee of HBR. The concentrations are much lower below the mean Hc surface (1658 m MSL), indicating that the bulk of plume material was transported above Hc up and over the ridge.

Table 3. Ten Highest χ/Q Observed SF_6 Concentrations at HBR

Exp No.	Hour End	χ/Q ($\mu s/m^3$)	Zr** (m)	Hc (m)	Zmax (m)	U(Zr) (m/s)	σ_v(Zr) (m/s)	σ_w(Zr) (m/s)	N (1/s)	d (m)
07	07	91.8	64	41	74.9*	1.7	.403	.146	.0309	1020
07	05	82.4	60	40	97.4	1.7	.479	.179	.0319	762
05	06	81.1	70	71	97.4	1.3	1.011	.345	.0327	762
15	03	55.9	42	43	79.1	2.1	.347	.121	.0544	1238
04	03	51.6	62	42	79.5	1.7	.939	.359	.0229	643
15	11	47.9	70	5	85.8	4.6	.576	.442	.0000	956
07	04	44.1	70	39	76.1*	1.8	.409	.163	.0268	927
11	09	42.2	49	30	72.4*	2.3	.463	.205	.0269	1024
10	02	41.9	73	47	76.1*	1.3	.362	.138	.0218	927
09	06	40.1	57	-	83.7*	-	-	-	-	1013

*Concentrations measured in lee of HBR.
**Release height plus plume rise.

Table 4 lists the ten highest observed CF_3Br concentrations (as normalized χ/Q) measured at HBR along with the appropriate release and meteorological information. For CF_3Br, the highest concentrations occurred when Zr < Hc. Releases below Hc tended to stagnate, producing high concentrations on the windward side of the ridge at typically Hc > Zmax > Zr. Occasionally plume material was slowly transported up and over the ridge after

Table 4. Ten Highest χ/Q Observed CF_3Br Concentrations at HBR

Exp No.	Hour End	χ/Q ($\mu s/m^3$)	Zr (m)	Hc (m)	Zmax (m)	U(Zr) (m/s)	σ_v(Zr) (m/s)	σ_w(Zr) (m/s)	N (1/s)	d (m)
06	08	444.7	37	48	30.4	1.1	1.243	.390	.0248	653
04	07	404.7	32	70	31.9	1.3	.990	.361	.0338	485
07	07	404.2	27	41	21.6	0.6	.485	.120	.0529	651
05	06	392.6	32	71	30.1	1.3	.960	.339	.0435	547
08	04	328.7	43	68	21.6	1.0	.342	.125	.0339	579
07	03	259.4	37	50	79.4	0.5	.405	.186	.0221	780
07	08	217.5	22	42	30.4	0.9	.379	.122	.0827	653
07	06	184.9	27	47	21.6	0.6	.471	.116	.0486	653
11	03	166.0	37	64	52.9	0.9	.937	.096	.0449	770
06	07	144.1	42	44	57.5	1.1	1.069	.374	.0248	611

impingement on its windward side. However, if the winds near the release had a substantial component parallel to the ridge, then the plume stayed below the crest.

The CF_3Br emissions released well below Hc produced the highest concentrations observed during the three CTMD experiments. The results at HBR are quite different than those experienced at CCB. At HBR the flow below Hc was "blocked" and the tracer gas pooled against the ridge and subsequently was either lifted over the top or was transported parallel to the ridge line to the south. At CCB the flow well below Hc traveled around the sides of the hill and, consequently, tracers released well below Hc produced low concentrations.

The observed hourly averaged CF_3Br concentration distribution for Experiment 6 Hour 8 is shown in Figure 4. The CF_3Br tracer gas was released 100 m from the base of the ridge at a release height 20 m above the ground. The release base elevation was 17.4 m above the zero elevation of the hill coordinate system, so the net release height corresponds to the 37.4 m height level on the ridge. The hourly average Hc value is 48 m; thus, this hour is representative of flow below Hc. Sonic anemometer measurements indicate more than 90 degrees of wind direction shear between 5 and 40 m. The propeller-derived wind direction profile exhibits large wind directional shear below 30 m. The largest observed concentrations are found near the

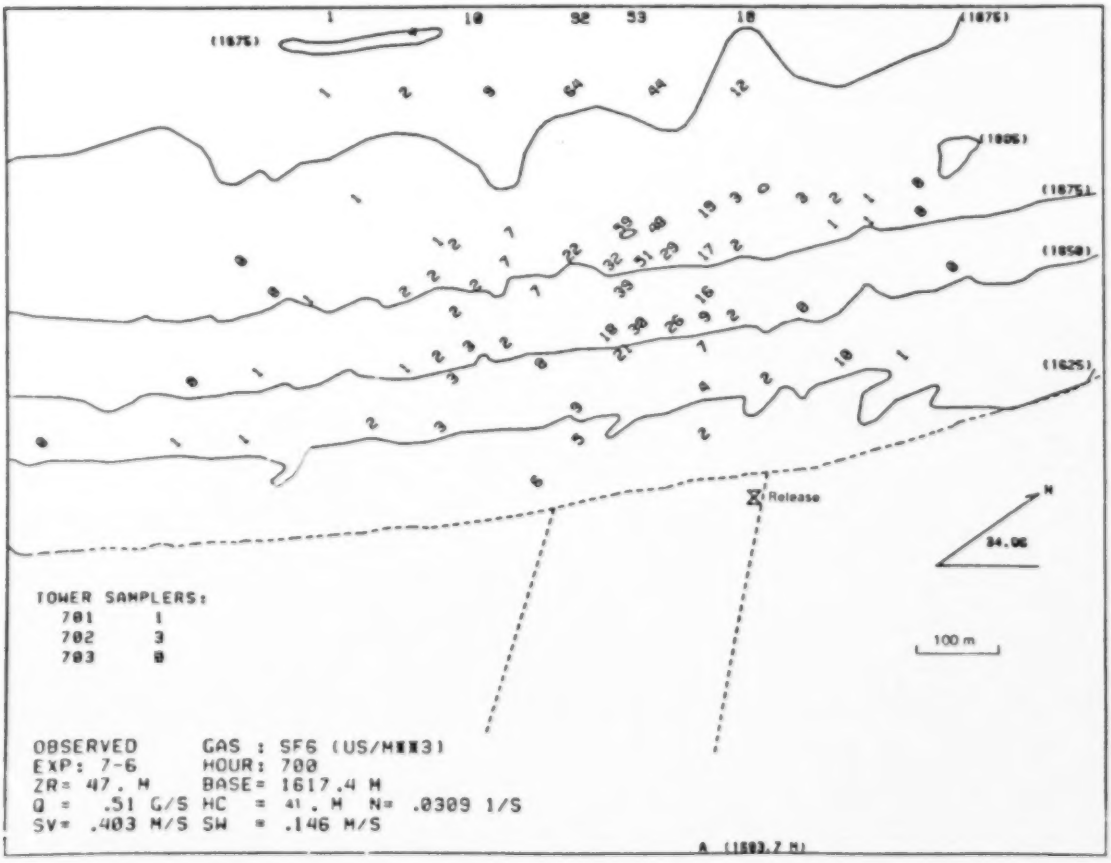

Figure 3. One-hour average observed SF_6 concentrations scaled by emission rate ($\mu s/m^3$). Experiment 7, 14 October 1982, 0600-0700 MDT.

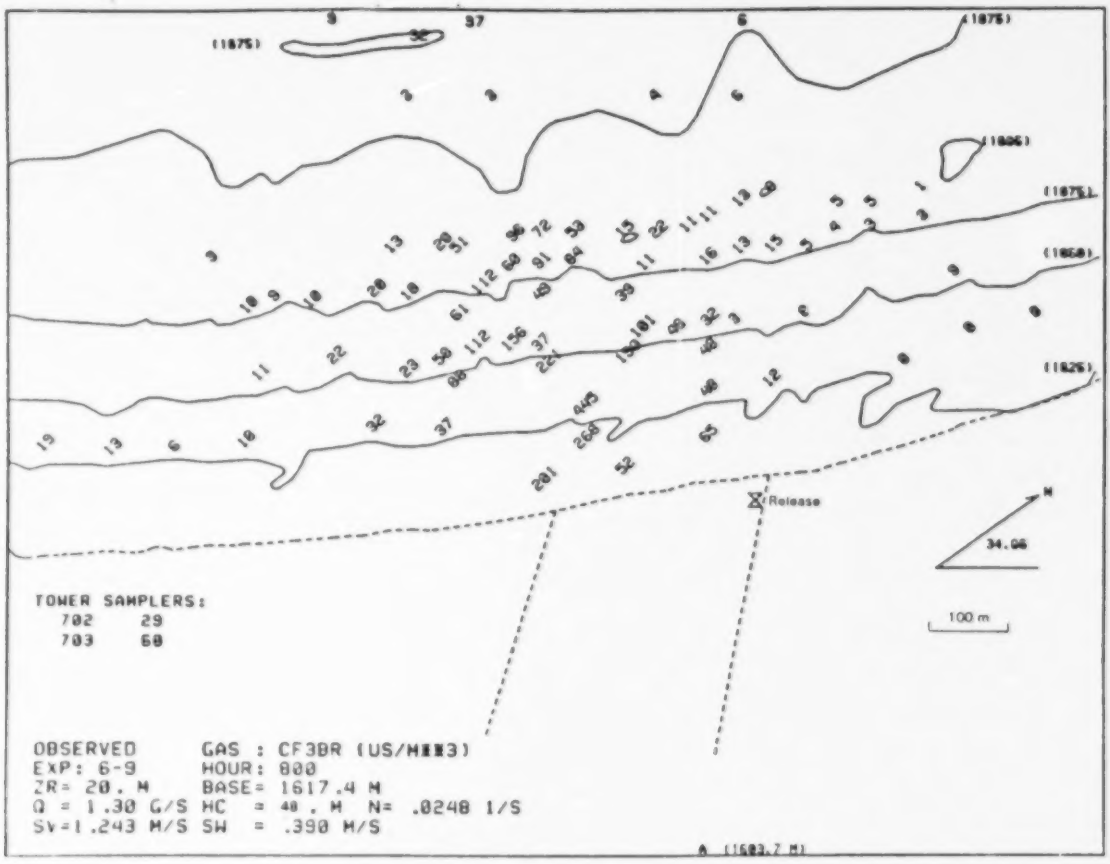

Figure 4. Hourly average observed CF_3Br concentrations scaled by emission rate ($\mu s/m^3$). Experiment 6, 13 October 1982, 0700-0800 MDT.

bottom half of the sampler array at an elevation that is less than Hc. The maximum observed concentration (445 $\mu s/m^3$) is found 7 m below the local release height at an elevation of 30.4 m. This is the largest observed normalized concentration found in the CTMD modeling data set. This maximum concentration is confirmed by a colocated sampler which measured 425 $\mu s/m^3$ for the same period. A sharp decrease of observed tracer concentrations is found above the mean Hc surface (1661 m MSL).

Full Scale Plume Study

The ten highest observed SF_6 and CF_3Br concentrations (as normalized X/Q) measured at the FSPS are presented in Tables 5 and 6. The FSPS tracer gas concentrations are considered preliminary and are presented here to illustrate the differences between the three sites. The SF_6 tracer gas and the oil-fog were released simultaneously from the 91.4-m stack. Because the lidar data are still in the processing stage, plume rise estimates have not yet been made. The CF_3Br tracer gas was released from the 150-m instrument tower (at 100, 125, or 140 m) located about 1.2 km east of the Tracy stack. The highest concentrations mainly occur when Zr < Hc for both SF_6 and CF_3Br. On average, Zmax > Zr for the SF_6 tracer hours; however, Zmax < Zr, on average, for the CF_3Br tracer hours.

Table 5. Ten Highest χ/Q Observed SF_6 Concentrations at FSPS

Exp No.	Hour End	χ/Q ($\mu s/m^3$)	Zr* (m)	Hc (m)	Zmax (m)	U(Zr) (m/s)	σ_v(Zr) (m/s)	σ_w(Zr) (m/s)	N (1/s)	d (m)
05	22	10.2	91.4	31	212.9	4.7	.978	.338	-	6922
13	09	8.3	91.4	182	172.8	1.5	.405	.099	.0250	4086
05	05	8.2	91.4	283	170.2	0.4	.420	.104	.0114	3191
02	05	8.0	91.4	201	75.5	2.9	.023	.161	.0305	3835
12	10	7.9	91.4	146	19.8	1.8	.541	.224	.0240	1645
11	06	7.5	91.4	214	115.4	1.3	.451	.117	.0260	4522
13	08	6.7	91.4	198	172.8	1.1	.629	.085	.0229	4086
05	06	6.5	91.4	279	170.2	0.2	.170	.068	.0200	4086
10	05	6.4	91.4	220	130.1	1.4	.305	.086	.0255	3191
07	07	5.5	91.4	289	180.9	2.6	.368	.152	.0250	5877

*Stack height; estimates of final plume height not yet available.

Table 6. Ten Highest χ/Q Observed CF_3Br Concentrations at FSPS

Exp No.	Hour End	χ/Q ($\mu s/m^3$)	Zr (m)	Hc (m)	Zmax (m)	U(Zr) (m/s)	σ_v(Zr) (m/s)	σ_w(Zr) (m/s)	N (1/s)	d (m)
12	09	35.1	100	393	164.3	0.5	.278	.066	.0333	4595
02	07	19.5	100	282	106.5	1.4	.077	.115	.0200	2391
04	02	13.4	100	92	2.7	1.8	1.167	.272	.0075	1532
13	03	12.8	100	234	199.6	2.5	.315	.121	.0313	5000
11	09	11.0	100	170	25.9	1.7	.460	.277	.0378	2923
13	09	11.0	100	152	43.5	1.3	.258	.094	.0273	2334
10	09	10.8	100	224	53.9	1.2	.275	.099	.0267	4101
10	08	10.6	100	214	43.5	0.5	.122	.085	.0200	2334
09	08	10.3	100	187	170.2	2.7	.718	.250	-	2028
10	06	9.8	100	676	170.6	0.7	.660	.076	.0233	1957

The hourly averaged observed SF_6 concentration distribution ($\mu s/m^3$) for Experiment 13 Hour 9 is presented in Figure 5. The SF_6 tracer gas and oil-fog were released from the Tracy stack at a height 91.4 m above the ground. The plume rise is estimated from photographs to be no more than one stack height in elevation; thus an effective stack height would be approximately 180 m. The hourly averaged Hc value is estimated to be 182 m; thus this hour illustrates transport along streamlines very near Hc. Observations indicate that as the plume approached "Beacon Hill", it split and traveled around the sides of the hill to the north and south. There was impingement on the southeast flank of Beacon Hill where the maximum observed concentration (8.3 $\mu s/m^3$) was measured. The plume also impinged to the north of Beacon Hill where the second highest concentration (8.0 $\mu s/m^3$) for the hour was observed. Filaments of plume material periodically traveled up towards the summit of Beacon Hill producing concentrations of 1.9 $\mu s/m^3$. Half-way through the hour, the plume shifted so that the main segment passed over the southern portion of Beacon Hill and the valley. Eventually the wind shifted so that by the end of the hour, the main body of the plume was traveling towards the west.

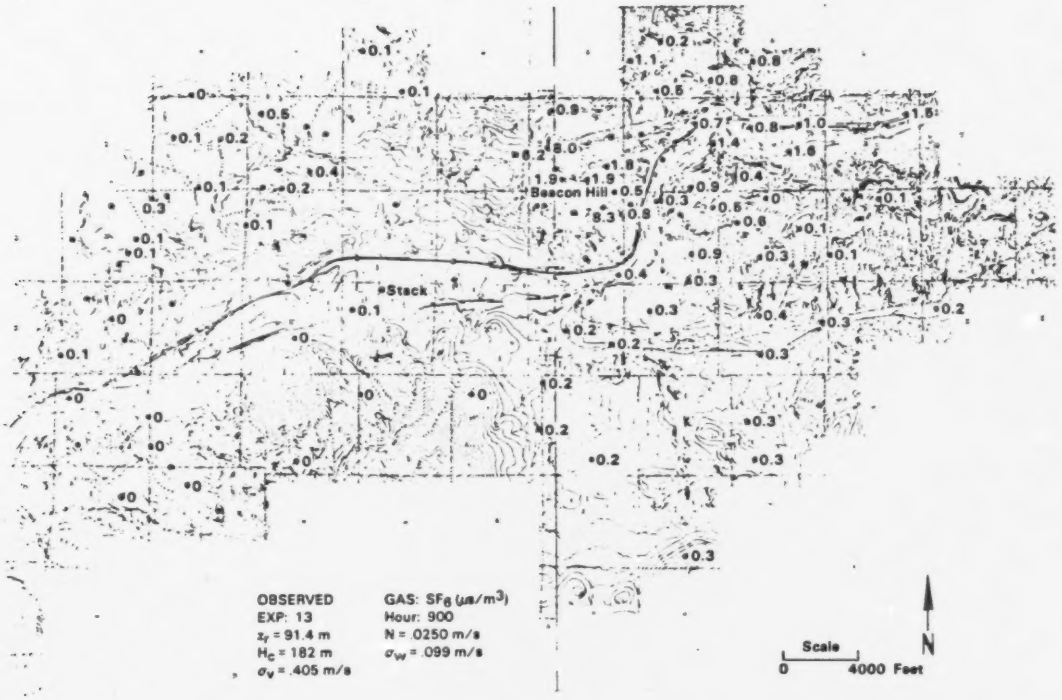

Figure 5. One-hour average observed SF_6 concentrations scaled by emission rate ($\mu s/m^3$). Experiment 13, 26 August 1984, 0800-0900 MDT.

CONCLUSIONS

The highest tracer gas concentrations observed at the three CTMD field sites support the concept of a dividing streamline separating a two-layer flow. At the CCB and Tracy sites the highest concentrations were measured when the tracer gases were released near the height of the calculated dividing streamline. Tracers released well below Hc were transported around the sides of the terrain and produced lower concentrations. In contrast, at the Hogback Ridge the highest concentrations were observed when CF_3Br was released in the blocked flow below Hc. These conditions produced the highest concentrations observed at the three CTMD field sites. Tracers released above Hc were transported up and over the terrain and produced ground-level concentrations near the top or on the lee side.

The height of the dividing streamline was calculated according to Equation 4 using observed wind and temperature profiles. Mathematical and fluid modeling studies (e.g., Strimaitis et al., 1983; Hunt et al., 1979; Snyder and Hunt, 1984) suggest that impingement (Zr ~ Hc) concentrations can be approximated by centerline concentrations that would exist without the presence of the hill. Hence, accurate estimates would require information on the plume distribution (e.g., σ_y — including meander effects, and σ_z) upwind of the terrain. Work is in progress (Strimaitis et al., 1984) on modeling concentrations at ridge settings in order to better account for the phenomena of blocked flow.

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